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Energy Demand Response of Process Systems through Production Scheduling and Control

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Abstract: Demand response has become a topic of significant research, development, and deployment over the last few years. The energy demand management is a critical task in industrial process systems for the potential benefits to be realized by promoting the interaction and responsiveness of process operation. However, the dynamic behavior, especially transition trajectories, of the underlying process is seldom taken into account during this task. Furthermore, the incorporation of energy constraints related to electricity pricing and availability is one of the key challenges in this process. The purpose of this study is thus to present a novel optimization formulation for energy demand management in dynamic process systems that takes transition behavior and cost explicitly into account, while simultaneously handling time-sensitive electricity prices. This is accomplished by bringing together production scheduling and transition control through a real-time optimization framework. The dynamic formulation is cast as a mixed-integer nonlinear programming problem and demonstrated using a continuous stirred tank reactor example where the energy required is assumed to be roughly proportional to the material flow.

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1. INTRODUCTION

In recent years, demand-side activities have been in the spot light in all energy policy decisions due to the significant benefits that can be realized - both at the economic and operational levels – through demand-side management. Indeed, the market price of electricity is the dominant incentive and influences heavily the electricity consumption of industrial customers. Typical examples of time-sensitive electricity prices are time-of-use (TOU) rates and real-time prices (RTP). While TOU rates are usually specified in terms of on-peak, mid-peak and off-peak hours, RTP vary every hour and are quoted on a day-ahead or hourly basis [2]. Furthermore, one important component of the current and future power systems is the concept of demand response (DR), which focuses on the operational level. DR is achieved through mechanisms that discourage the energy load when the real-time price is high and vice versa. Although the economic potential of DR for industrial processes has been recognized in a number of recent studies [3-5], it should be noted that since DR requires, by definition, varying production levels, the consideration of transition behaviour between different operating modes is an issue that remains open.

An examination of the existing research on DR for industrial processes shows that the transition behaviour problem has not been fully explored or adequately addressed in the literature. Examples of important contributions in this area include the work of Mitra et al. [2], where an optimal production planning model for continuous power-intensive processes under time-sensitive electricity prices was developed. The focus of that study was mainly on minimum stay constraints for describing ramp-up transition and rate of change constraints for restricting transitions between operating points. The dynamic profile of the transition behaviour, however, was not taken into account in the optimization formulation. In another study, Mendoza-Serrano and Chmielewski [6] illustrated the potential opportunities of DR for a chemical manufacturing facility, which was assumed to operate at continuously changing production levels. The discrete transitional behaviour between the different operating modes was not considered in the problem formulation or solution.

From the standpoint of DR for industrial processes, the goal lies primarily in determining the optimal production levels at each time instant. The control problem is thus closely related to demand responsiveness given that the major task of controllers is to determine the optimal values of manipulated and controlled variables in order to achieve different production levels. Generally, production scheduling and control problems can be addressed simultaneously or sequentially [7, 8]. Some early attempts to tackle simultaneous scheduling and control problems can be found in the literature [9-11]. However, to the best of our knowledge, energy consumption was not considered in these studies. In addition, one of the most challenging aspects of plant scheduling is undoubtedly the incorporation of energy supply constraints related to electricity pricing and availability.

Motivated by these considerations, the objective of this work is to present a new optimization formulation for energy demand management in process systems that considers

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explicitly dynamic transition behaviour and cost, and simultaneously handles time-sensitive electricity prices. The presented study is explorative, focusing on demand response which is realized through a combined production scheduling and control approach which into account the dynamic profile of the transition process as well as time-varying electricity prices. The proposed formulation is illustrated using a conceptual case study involving a continuous stirred-tank reactor (CSTR) process example where the energy required is assumed to be roughly proportional to the material flow and the process has to satisfy an hourly demand for the product.

2. FORMULATION OVERVIEW

2.1 Problem Definition

The conceptual production system with a set of components considered for demand response in this study, are shown in Figure 1 below.

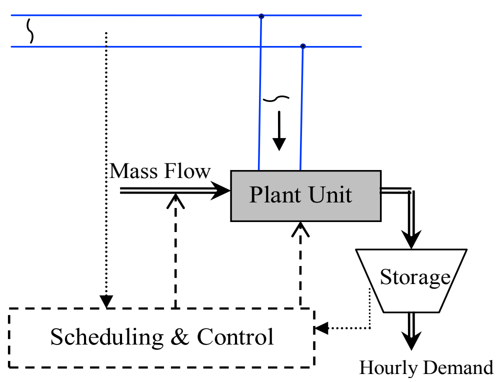

Figure 1. A schematic representation of the problem formulation.

The system has to satisfy an hourly demand of the product, and a particular storage unit is installed to provide flexibility. The electricity prices vary on an hourly basis and the demand response decisions do not influence the electricity prices. A lower bound for the product hourly demand - expressed as a constant rate - is specified. Steady-state operating modes for different production levels are also specified a priori, as well as the price of the inventory and raw material costs. The problem then consists of the simultaneous determination of the operating mode for the plant (i.e., production level) and the control profile for the production level changes. The main objective is to minimize the total production cost, which includes the transition cost (i.e., raw material waste and electricity waste during the transitions), inventory cost, and electricity cost.

2.2 A Combined Scheduling and Control Approach

The dynamic process model is incorporated into the constraints of the scheduling problem resulting in a mixed integer dynamic optimization (MIDO) problem. Solution methods of general MIDO problems are presented in a number of papers [12-15]. A general decomposition-based framework was built by Allgor and Barton [13], and Flores-Tlacuahuac and Biegler [14] proposed a methodology to transfer the MIDO problem into an MINLP through the discretization of the dynamic model. Terrazas-Moreno *et al.* [15] extended the work by Flores-Tlacuahuac and Grossmann [9] and proposed a Lagrangean decomposition strategy to simplify the scheduling and control problem. However, in the current work, to handle the dynamic optimization problem, the steady-state and transition states are treated differently.

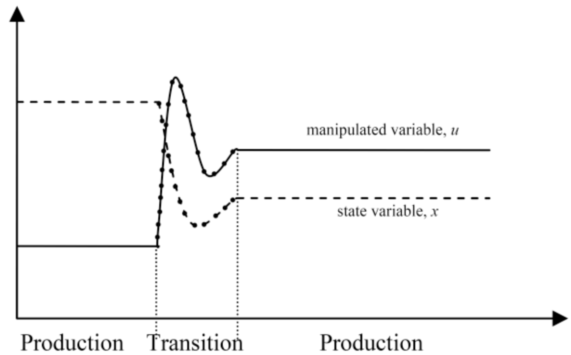

Figure 2. Dynamic system behaviour as production transitions between different operating modes.

As shown in Figure 2, the system states and the manipulated variables remain constant during the production period, while the manipulated variables change within the transition period and so do the system states. Given that the steady-state operating modes corresponding to different production levels are predefined, the steady-state values of the manipulated variables are thus known constants. However, in order to model the transition-state behavior, the transition period is discretized on the basis of the system sampling interval as shown in Figure 2. With a detailed plant model, the approximated transition behavior between different operating modes can then be calculated, and the control actions needed to drive the transitions can be computed off-line. Moreover, in the absence of a mathematical model, the transition profile can still be obtained from historical plant data. Generally, the transition profile between the same pair-wise operating modes should follow a similar trajectory. From this point of view, the key advantages of this method lie in the fact that the incorporated differential equations are transformed into to a set of data and that the transition times between different production levels are also known parameters. These aspects reduce the computational complexity of the combined scheduling and control problem.

3. MODEL FORMULATION

3.1 Scheduling Constraints

The plant unit has a set of discrete operating modes corresponding to different production levels, $m \in M$. For every time period (hour h), we introduce two binary variables, y_m^h and $z_{m,m'}^h$, and one continuous variable s^h , which define the mode assignment, transition status, and storage level, respectively.

Mode assignment constraints: The constraints for the mode assignment are given by the following:

$$\sum_{m \in M} y_m^h = 1 \qquad \forall h \tag{1}$$

$$\tilde{y}_m^h = y_m^{h-1} \qquad \forall m, h \neq 1 \tag{2}$$

$$\tilde{y}_m^1 = y_m^0 \qquad \forall m \tag{3}$$

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